Building and Environment 141 (2018) 182–192

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Assessment of the contributions of different flat roof types to achieving sustainable development

Salvador Guzmán-Sánchez[a], Daniel Jato-Espino[b,*], Ignacio Lombillo[c], Jose Manuel Diaz-Sarachaga[b]

[a] University of Cantabria, Civil Engineering School, 39005, Santander, Spain
[b] GITECO Research Group, University of Cantabria, Civil Engineering School, 39005, Santander, Spain
[c] Dept. of Structural and Mechanical Engineering, University of Cantabria, Civil Engineering School, 39005, Santander, Spain

ARTICLE INFO

Keywords:
Climate scenarios
Expert judgment
Multi-criteria decision analysis
Flat roofs
Sustainability

ABSTRACT

The sustainability of cities is being influenced by their roofs, which cover a high proportion of built-up areas and whose design is crucial to control their economic, environmental and social impacts in a context of urban sprawl and Climate Change. For this reason, this research developed a Multi-Criteria Decision Analysis (MCDA) methodology combining the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to support the selection of four representative flat roof types (self-protected, gravel finishing, floating flooring and green) according to their contribution to sustainability, based on their performance across a list of indicators aligned to the United Nations Sustainable Development Goals (SDGs). The analysis was carried out under three different climate scenarios (Mediterranean, Oceanic and Continental) and relied on the judgments provided by a panel of experts in the building sector to both refine and weight the proposed indicators. The results proved that green roofs were the most sustainable alternative for all the scenarios evaluated, by virtue of their insulation, recycling, cost, energy, water and ecosystem-related benefits. Consequently, this type of roof emerges as a multifunctional solution to be strongly considered in the design of planning strategies seeking urban regeneration.

1. Introduction

Roofs occupy about 20–25% of urban surfaces [1], whilst the buildings they cover account for 40% of total energy consumption worldwide [2] and 36% of European greenhouse gas emissions [3]. As such, roofs are key drivers for ensuring sustainable economic development, environmental protection and social welfare, especially in a context of urban sprawl and Climate Change whereby more than half of the world's population live in cities [4] whose resilience is being exceeded by the intensity of weather events [5].

One the one hand, urbanisation favours the presence of impervious surfaces and reduces evapotranspiration, exacerbating the Urban Heat Island effect [6] and the warming of cities [7]. The presence of impervious areas also has relevant impacts on water quality and quantity [8], whilst the car-dependent lifestyle derived from urban population growth favours air pollution [9]. On the other hand, global temperature is forecasted to rise in the future, particularly in urban areas as a result of anthropogenic development [10]. There is also evidence of an increase in extreme rainfall intensity in recent years, boosting the magnitude and frequency of flash floods [11].

The design of roofs impacts on these phenomena, influencing the resilience of cities to alterations in temperature, water-related processes, energy and air quality [12]. Furthermore, roofs can also contribute to economic growth, environmental safeguard and human wellbeing [13]. Therefore, the planning of these elements provides a multifaceted opportunity to help meeting some of the United Nations Sustainable Development Goals (SDGs) [14], which seek to protect the planet and ensure prosperity for all.

The literature review, which is addressed in section 2, revealed a knowledge gap in the selection of roofs according to the principles of sustainable development using indicators that contribute to achieving the SDGs. The representativeness of the roof types analysed and the evaluation of different climate and weighting scenarios were other aspects having room for improvement. Hence, this study emerged to jointly address all these issues by assessing four characteristic flat roofs across a list of sustainability indicators under three climate types, including a sensitivity analysis to guarantee the reliability of the results obtained when prioritising different roof-related facets. Consequently,

* Corresponding author.
E-mail address: jatod@unican.es (D. Jato-Espino).

https://doi.org/10.1016/j.buildenv.2018.05.063
Received 3 April 2018; Received in revised form 30 May 2018; Accepted 31 May 2018
Available online 02 June 2018
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the main theoretical contribution of this investigation consisted of the development of an ad-hoc methodology to measure the performance of different roofs using multiple conflicting variables. Still, the proposed approach might also be easily adapted to the characteristics of other elements, such as vertical and indoor horizontal systems, providing a practical tool to appraise the design of buildings and support the adoption of urban planning strategies aligned with the SDGs.

2. Literature review

Several investigations have been conducted over the past two decades to support the selection of roofs using multiple criteria. Nassar et al. [15] developed a tool to evaluate asphalt, plastic and metallic roofs in terms of durability, insulation, permeability, maintenance, warranty, compatibility and serviceability. Abeysundara et al. [16] presented a lifecycle-based matrix to support the choice of sustainable materials for two roof types (asbestos sheet and clay tile) according to their affordability, embodied energy, environmental impacts, comfort, aesthetics, strength, durability and constructability. Similarly, AL-Nassar et al. [17] evaluated six wall-roof systems using a lifecycle impact index aligned with the triple bottom line of sustainability. Collier et al. [18] assessed the sustainability of three roofing technologies (reflective, vegetated and solar roofs) considering their costs, resource usage, environmental impacts and welfare benefits. Canto-Perello et al. [19] appraised three roofs formed of prefabricated concrete, steel and laminated wood structures in terms of costs, emissions, energy, fireproofing, use of local materials and aesthetics. Loikkanen et al. [20] analysed different energy solutions for a glass roof using their internal rate of return, energy efficiency, CO_2 emissions and attractiveness as decision criteria.

The literature also contains more specific research in terms of either the alternatives or criteria evaluated. Liu et al. [21] developed a decision-making model to support the adoption of energy-saving designs for residential buildings, demonstrating the potential of green roofs for this purpose. Gagliano et al. [22] compared the energy savings and environmental advantages provided by three alternatives (conventional, cool and green roof), based on dynamic simulations under temperate climate conditions. Kalibatas and Kovaitis [23] focused on the selection of waterproofing membranes for inverted flat roofs through additive weighting methods and game theory rules. Szafranko [24] applied an indicator-based methodology to evaluate two roof girders according to installation, structural and recyclability variables. Finally, several studies have appraised green roofs in comparison with other green infrastructure systems, such as bioretention cells, infiltration trenches or permeable pavements [25–27].

3. Methodology

The main steps of the proposed methodology are outlined in Fig. 1. From a conceptual point of view, the approach taken consisted of establishing a series of energetic, hydrologic, environmental, social, economic and structural indicators to assess the sustainability of several flat roof types under different climate scenarios. From a technical perspective, this was accomplished using Multi-Criteria Decision Analysis (MCDA) methods, which enabled assessing the performance of different roofs and ranking them across a list of weighted indicators refined based on the opinions collected from a panel of experts in the building sector.

3.1. Definition of the initial list of sustainability indicators

An indicator can be defined as a measure providing guidance about how to value a certain parameter [28]. In this case, an initial set of indicators as listed in Table 1 was proposed to assess the sustainability of different flat roof types according to the principles included in the Sustainable Development Goals (SDGs).

The Albedo coefficient (I_1) represents the portion of solar radiation reflected to the atmosphere [29]. Hence, the greater the Albedo of a roof, the less it is heated by insolation. Consequently, this indicator is related to the impacts of roofs on the warming of buildings, which might help improving the resilience against climate hazards considered in SDGs 1 and 13.

The second indicator (I_2) concerned the thermoregulatory potential of roofs and their capacity of attenuating local temperature. This factor might have a positive effect on the production of solar energy, since high temperatures reduce the performance of photovoltaic cells. Therefore, the indicator of solar power can contribute to meeting the targets of energy efficiency contemplated in SDG 7.

The materials forming the layers of roofs might help capturing atmospheric carbon, such that they act as a natural sink (I_3). This aspect is in line with some of the targets included in SDGs 3, 11 and 12, focused on reducing the presence of atmospheric hazards to protect human health, as well as controlling environmental contamination in cities.

The next two indicators (I_4 and I_5) consisted of the embodied carbon and energy associated with roofs, from the extraction of raw materials to the construction of the structure. Hence, these indicators, as well as that concerning the use of recycled materials (I_{11}), are related to SDGs 3, 7, 8, 11 and 12, which deal with the effects of resource efficiency on energy and environment.

Rainfall was added to the list of indicators through the benefits of roofs in terms of runoff (I_6), pollution (I_7) and temperature (I_8) reduction. These aspects can be translated into flood mitigation, rainfall purification and protection of flora and fauna against high runoff temperatures, which are concepts extremely linked to the water-related issues highlighted in SDGs 1, 3, 6, 11, 13, 14 and 15.

Biodiversity (I_9) and agricultural productivity (I_{10}) referred to the potential of roofs for supporting the presence of animal and plant species and the growth of crops, respectively. These indicators may aid to meet several targets seeking the achievement of sustainable food, communities and life in SDGs 2, 11 and 15.

Building insulation in thermal and acoustic terms was represented through I_{12} and I_{13}, which served to value the role played by different roofs when alleviating adverse external weather and noise conditions. Consequently, both indicators are associated with SDGs 7 and 11 in what concerns the safeguarding of the energy efficiency and adequate services of buildings.

Life cycle cost (I_{14}) was an indicator devoted to measure the economic expenses stemming from the construction, maintenance and eventual demolition of roofs, according to their expected lifetime. As such, this indicator is aligned with the principles of sustainable economic growth and urban development highlighted in SDGs 8 and 11.

The social dimension of sustainability was represented by an indicator concerning the contribution of roofs to improving the aesthetical perception of their surroundings (I_{15}). This aspect was expected to impact positively on the development of urban areas towards inclusive and pleasant places to live in, as expressed in the SDG 11.

Finally, the last two indicators accounted for functional characteristics of roofs, either in the form of the dead load transmitted to the structure below (I_{16}) or the protection of the waterproofing membrane (I_{17}). These factors can help achieving safe and controlled living and working environments, as specified in SDGs 8 and 11.

Some of these indicators depended on the climate conditions affecting roofs, such as precipitation, temperature and solar irradiance. To enable the accurate characterisation of different roofs across these weather-based indicators, a trio of scenarios was defined to represent some of the most characteristic types of climate in Europe.

3.2. Climate scenarios

Climate is a crucial factor in the assessment of roofs in terms of sustainable development. This study was undertaken under three different weather scenarios, coinciding with the three main types of

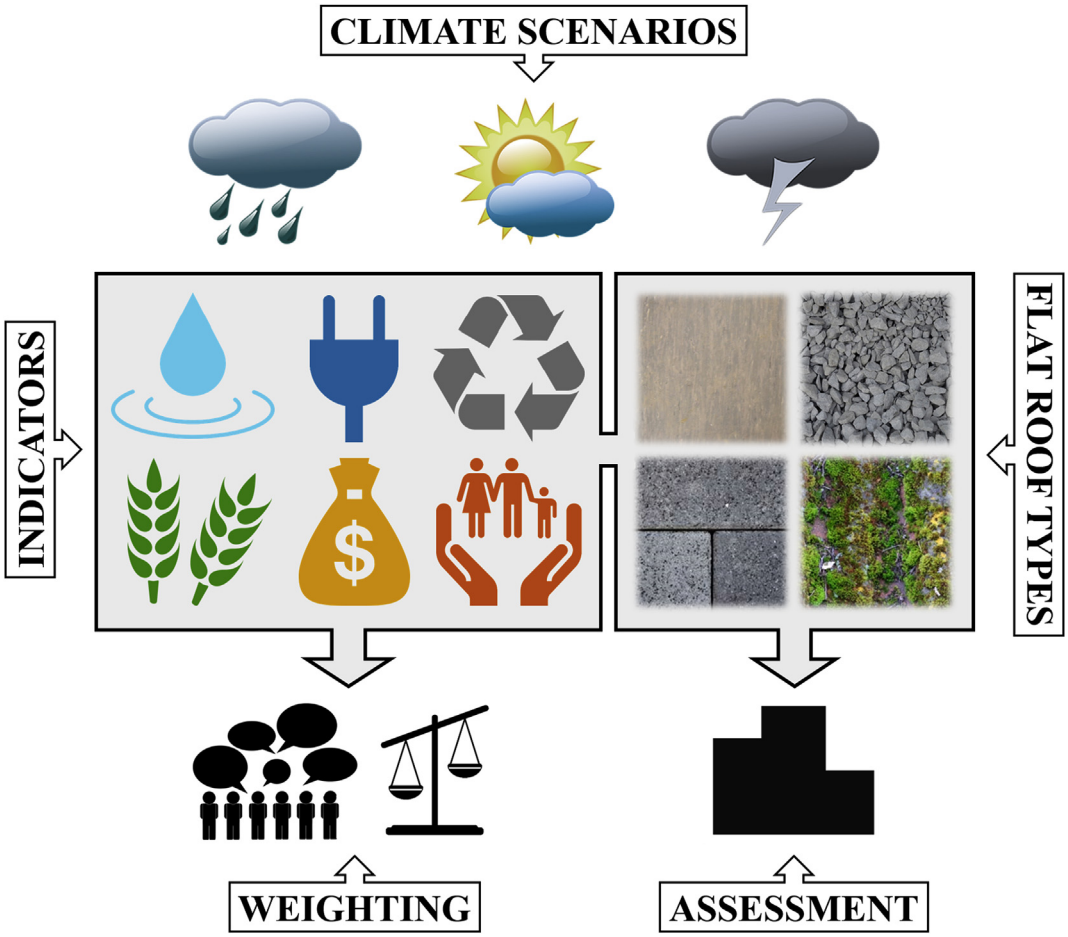

Fig. 1. Outline of the methodology designed to assess the contribution of different flat roof types to sustainable development.

Table 1
Initial list of indicators proposed to assess the sustainability of flat roofs and links to the Sustainable Development Goals (SDGs).

I_j	Indicator	Units	SDGs
I_1	Albedo coefficient	Dimensionless	1, 13
I_2	Solar power	%	7
I_3	Carbon sequestration	g C/m^2	3, 11, 12
I_4	Embodied carbon	kg CO_2 eq./m^2	7, 8, 11
I_5	Embodied energy	MJ/m_2	3, 8, 11, 12
I_6	Runoff attenuation	%	1, 6, 11, 13, 15
I_7	Water purification	Score	3, 6, 14
I_8	Reduction of runoff temperature	°C	14
I_9	Biodiversity	Yes/No	11, 15
I_{10}	Agricultural productivity	Yes/No	2
I_{11}	Recycled materials	%	8, 12
I_{12}	Thermal insulation	cm	7, 11
I_{13}	Noise control	t/m^3	11
I_{14}	Life cycle cost	€/m^2	8, 11
I_{15}	Aesthetics	Score	11
I_{16}	Dead load	kN/m^2	11
I_{17}	Roof protection	± °C	8, 11

climate in Spain [30]: Oceanic, Continental and Mediterranean. Each climate scenario was associated with a representative city (Fig. 2), in order to obtain the set of parameters required to implement the methodology in a particular area.

The first type of climate is found in the Mediterranean and South-Atlantic coast of Spain. The precipitation conditions in these areas range from scarce to moderate, with hot summers and mild winters. Valencia epitomised the characteristics of the Mediterranean climate, reaching high figures in terms of average maximum temperature (23 °C) and hours of solar radiation (2696) per year. The annual mean precipitation in this city is 475 mm, with an average of 46 rainy days (≥1 mm).

The Oceanic climate is typical in the North of Spain, consisting of high levels of precipitation regularly distributed throughout the year and mild and narrow ranges of temperature, especially in coastal areas. The reference city for this type of climate was Santander, which highlights by having average values of annual precipitation and maximum temperature of 1200 mm and 18.5 °C, respectively. The approximate annual number of rainy days in Santander is 124, with 1649 h of solar radiation per year.

Finally, the interior regions in Spain belong to a Continental climate, characterised by scarce rainfall and temperatures with large thermal amplitudes, including warm summers and cold winters favoured by the insolation of these areas from the sea. Madrid was selected as a representative for this climate, a city with 371 mm of precipitation based on a number of 55 wet days per year. The average maximum temperature in the city is 21.1 °C, whilst the annual number of hours of solar radiation amounts to 2749.

The description provided about these climates demonstrated the variety of rainfall and temperature conditions covered by the three cities selected as representatives. The combination of the indicators listed in Table 1 with the proposed climate scenarios provided a solid framework to assess the contribution of any type of roof to sustainability.

3.3. Description of the flat roof types selected as alternatives

The alternatives proposed to undertake this evaluation were

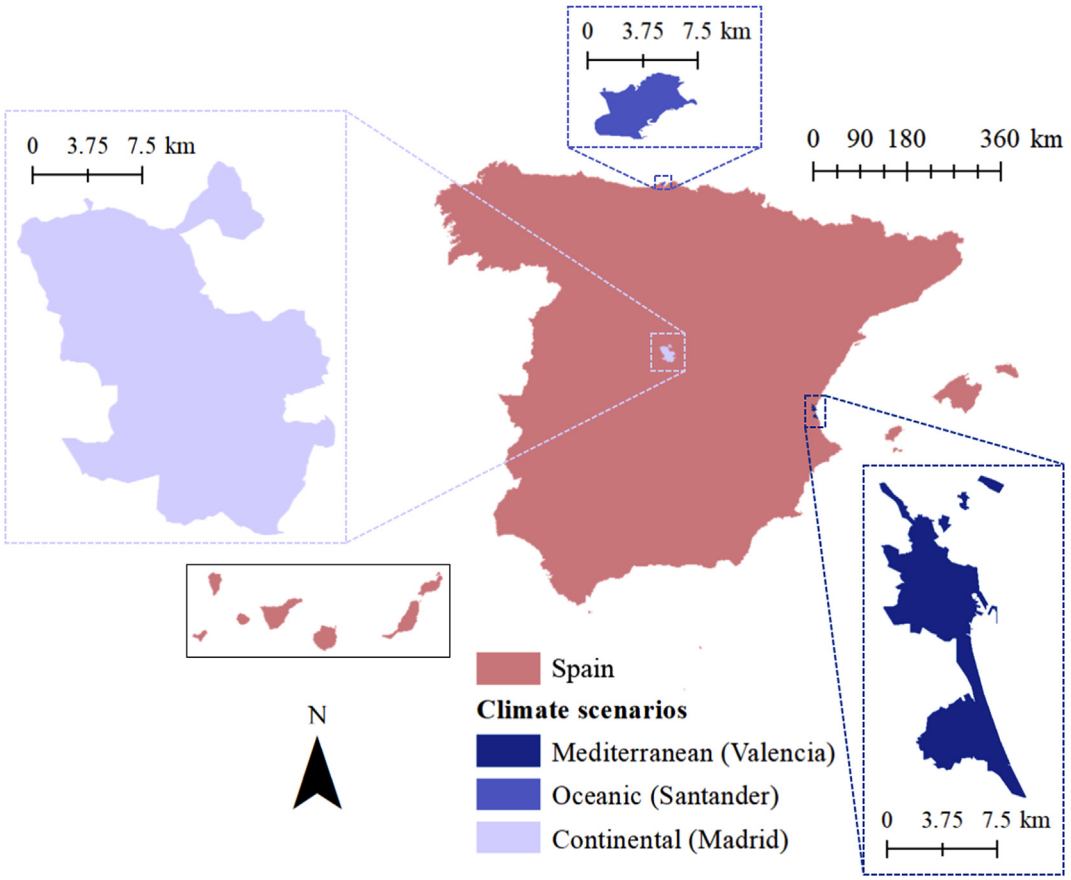

Fig. 2. Situation map of the cities used as representatives for the three climate scenarios considered: Continental (Madrid), Oceanic (Santander) and Mediterranean (Valencia).

selected to represent the most widely used types of flat roofs, resulting in the four cross-sections illustrated in Fig. 1: self-protected, gravel finishing, floating flooring and green. Some of the layers forming these roofs were the same in all cases, such as thermal insulation and cellular concrete for slope screed. The first consisted of rigid foam panels of Extruded Polystyrene (XPS), whose thickness depended on the insulation requirements for each climate scenario. These roofs were sloped using a 10 cm layer made of cellular concrete with recycled aggregates, including an adequate termination to support either the vapour barrier or the waterproofing membrane. In this sense, the four types of roofs laid on the same structural system, a unidirectional slab formed of reinforced concrete beams and concrete hollow blocks, with a 5 cm compression layer. Considering a 5 m span, the common loads considered in the structural design of roofs and the limit states under bending, shear, deflection and cracking, the thickness of the deck was 20 cm in all roofs.

The first cross-section in Fig. 3a) corresponds to a typical design for industrial uses, where flatness, low weight, simplicity and ease of construction are sought. The top layer of the self-protected roof was a white synthetic waterproofing membrane of plasticised Polyvinyl Chloride (PVC), manufactured through a calendaring process and reinforced with a polyester fibre mesh. This membrane was resistant to weathering and solar radiation, having a weight of 2.5 kg/m^2 [31]. A vapour barrier made of transparent Low Density Transparent Polyethylene (LDPE), with a thickness of 0.2 mm and a weight of 0.18 kg/m^2 [32], was included between the thermal insulation and the concrete for slope screed.

The roof shown in Fig. 3b) was non-trafficable due to its gravel finishing, except for repair or maintenance purposes. This protection layer was made of white aggregates with a diameter between 16 and 32 mm, a density of 20 kN/m^3, a thickness of 7 cm and a slope between 1 and 3%, in order to prevent material displacements [33,34]. Below was placed an anti-punching separation layer of non-woven geotextile formed by 100% Polypropylene (PP), with a weight of 250 g/m^2 [35]. The waterproofing membrane was similar to that defined for the self-protected roof, although there was no colour requirement in this case due to the position of the layer [36].

The floating flooring roof represented in Fig. 3c) consisted of a set of concrete floor tiles placed on a series of plots, leaving open joints and enabling water filtering [33]. This system creates a ventilated air chamber between the protection and insulation layers. The floor tiles were made of white concrete with recycled aggregates, having a thickness of 4 cm and a density of 25 kN/m^3 [34,37]. The plots were adjustable supports of 100% recyclable propylene copolymer, with a range of heights between 122 and 197 mm and a base with a diameter of 186 mm [38]. The distribution of the loads transmitted by the plots to the thermal insulation was guaranteed by a 1.5 cm layer of mortar with a density of 20 kN/m^3 [34] and a fiberglass mesh to provide flexural and cracking resistance. Besides, a LDPE separation layer with a thickness of 0.2 mm and a weight of 0.18 kg/m^2 [32] was included below the mortar to prevent its potential incompatibility with the thermal insulation.

The green roof depicted in Fig. 3d) was extensive, which corresponds to substrate thicknesses below 20 cm and small-sized vegetation [39]. The vegetation in this roof consisted of Sedum plants with a weight of 0.12 kN/m^2 [40], ensuring their applicability in the three climate scenarios considered due to their ease of growth and resistance to water scarcity, solar radiation and high temperature [33]. The substrate was formed of recycled aggregates, compost and inert soil in different proportions [41–43]. This layer had a saturated unit weight of 20 kN/m^3 [34] and a thickness of 10 cm to enable the plants taking root successfully. A separation and filtration layer consisting of a PP-based

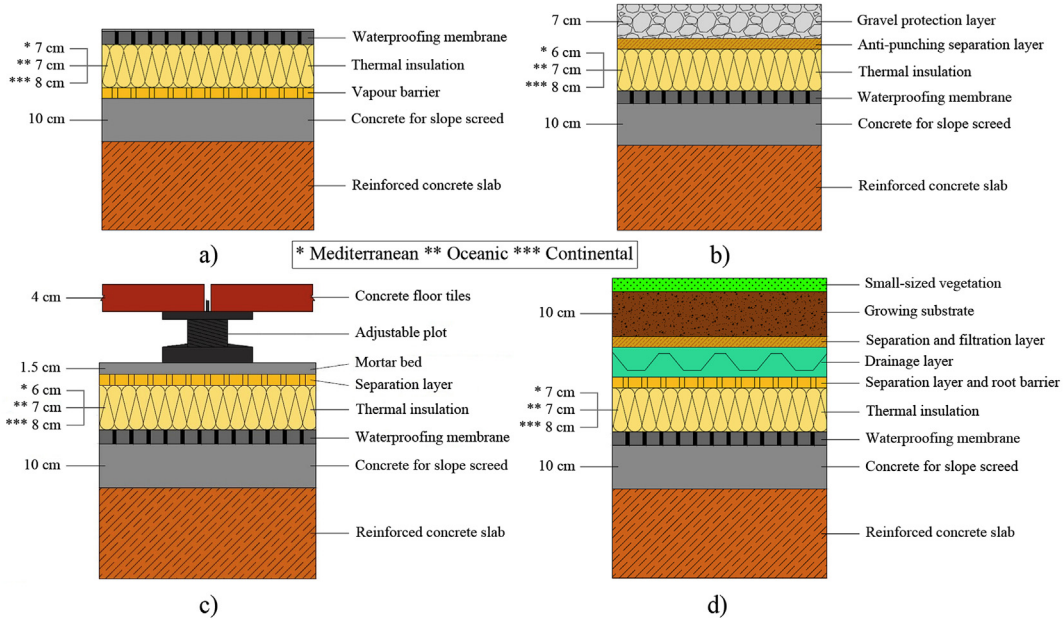

Fig. 3. Cross-sections of the four types of flat roofs selected as alternatives a) Self-protected roof b) Gravel finishing roof c) Floating flooring roof d) Green roof.

geotextile with a weight of 300 g/m^2 [44] was placed between the substrate and the drainage layer, made of a 60 mm High-Density Polyethylene (HDPE) with a weight of 1.75 kg/m^2 [45]. In addition, a 0.5 mm thick weatherproof polyethylene sheet with a weight of 0.475 kg/m^2 [46] was included below to prevent the perforation of underlying layers by the roots.

The description of these four alternatives, coupled with the definition of the indicators shown in Table 1 and the climate scenarios represented in Fig. 2, provided a complete characterisation of the MCDA problem concerning the sustainability-based assessment of different flat roof types.

3.4. Multi-Criteria Decision Analysis (MCDA)

The inclusion of MCDA enabled the evaluation of flat roofs across the indicators and climate conditions proposed. The framework designed for this purpose was based on the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), whose combination has been previously recommended for the field of building and structures due to their simplicity and ease of application [47]. Both methods were implemented after refining the initial set of indicators according to the feedback received from a group of building-related experts.

3.4.1. Refinement of the initial list of indicators

To ensure the soundness and validity of this investigation, a questionnaire based on the original list of indicators in Table 1 was prepared to enable its subsequent refinement and weighting. Although face-to-face interviews might have been a better approach to discuss the convenience of the indicators in depth, this course of action requires a degree of commitment and time investment on the part of the addressees that may have hindered their participation due to its lack of flexibility [48].

The questionnaire was addressed to a group of 50 experts, a figure within the range of minimum values commonly recommended to form representative panel sizes [49]. These experts were selected according to their recognition and background in the aspects addressed in Table 1, in order to guarantee a suitable and comprehensive processing of the indicators. Hence, they were professionals with deep knowledge and skills in different areas related to the building industry, including structures, energy efficiency, green roofs and/or planning and management of urban areas. Their practical experience varied between 5 and 44 years, with most of them within the range from 10 to 25 years, whilst their origin included the academy (52.08%) and construction sectors (10.42%), as well as private research centres (10.42%), different manufacturers of materials (6.25%) and associations to foster cooperation between all the parties involved (20.83%).

The questionnaire was prepared in spreadsheets, in order to use a familiar format for all the addressees. The first sheet included general information about the aim of the study and the instructions to fill the questionnaire in correctly. A brief definition of each indicator was provided in the next sheet, anticipating the last step in which the experts had to express their opinions about the importance of the elements in Table 1 according to four-level dropdown lists: very important (VI), important (I), slightly important (SI) and unimportant (UI). This scale was adopted based on the difficulties found in previous experiences when collecting questionnaires with a high number of comparison levels and indicators [50,51]. The last sheet also left room for judging the original list of indicators in terms of completeness, such that the experts could suggest the removal and/or addition of some of them, as well as their weight in the case of new factors.

The responses collected from the panel of experts enabled producing a refined list of indicators, considering their opinions about how to evaluate the contribution of roofs to sustainable development comprehensively. Furthermore, their valuations regarding the importance of the indicators were used to determine their weights.

3.4.2. Weighting of the refined list of indicators

The weighting of the refined set of indicators was undertaken through the AHP method [52], which seeks to determine the relative importance between two elements according to a pairwise comparison scale. A simplified version of this scale was used to weight the indicators (Table 2), consistent with the reduced number of levels of importance considered in the questionnaires, which were four (VI, I, SI and UI) to facilitate their fulfilment by the experts.

The comparisons made across the refined list of indicators using Table 1 yielded a reciprocal comparison matrix $[M]$, whose validity was evaluated according to the Consistency Ratio ($C.\ R.$) (Eq. (1)). This term depends on the maximum eigenvalue (λ_{max}) and the size (s) of $[M]$, as well as on the average consistency index of a set of comparison matrices generated randomly ($R.\ I.$).

Table 2
Adapted scale to compare the relative importance between indicators.

Importance (I_{j_1} vs I_{j_2})	Value	Possible cases
I_{j_1} is three levels of importance above I_{j_2}	7	VI vs UI
I_{j_1} is two levels of importance above I_{j_2}	5	VI vs SI I vs UI
I_{j_1} is one level of importance above I_{j_2}	3	VI vs I I vs LI LI vs UI
I_{j_1} is at the same level of importance that I_{j_2}	1	VI vs VI I vs I SI vs SI UI vs UI
I_{j_1} is one level of importance below I_{j_2}	1/3	UI vs LI LI vs I I vs VI
I_{j_1} is two levels of importance below I_{j_2}	1/5	UI vs I SI vs VI
I_{j_1} is three levels of importance below I_{j_2}	1/7	UI vs VI

$$C.R. = \frac{\frac{\lambda_{max} - s}{s-1}}{R.I.} < 0.1 \tag{1}$$

Since the calculation of the importance of the indicators stemmed from the comparisons made by a group of experts, an additional mechanism was needed to synthetize them all into a single vector of weights. This was carried out through the distance-based aggregation method proposed by Jato-Espino [51], which starts by allocating weights to all the m experts according to the Euclidean distance between their pairwise comparisons $x_{I_{j_1}I_{j_2}}$, in order to give more importance to those proving to be more similar to the remaining respondents. Hence, the weight w_{e_k} of an expert was determined from their distance $d_{e_{k_1}e_{k_2}}$ to the remaining experts p, as expressed in Eq. (2).

$$w_{e_k} = \frac{1/\sum_{k=1}^{p} d_{e_{k_1}e_{k_2}}}{\sum_{k=1}^{p}\left(1/\sum_{k=1}^{p} d_{e_{k_1}e_{k_2}}\right)} \Leftrightarrow d_{e_{k_1}e_k} = \sqrt{\sum_{j=1}^{n}\left(\ln x_{I_{j_1}I_{j_2},e_{k_1}} - \ln x_{I_{j_1}I_{j_2},e_{k_2}}\right)^2} \tag{2}$$

The opinions provided by the experts were aggregated into a matrix formed of consensual comparisons $x_{I_{j_1}I_{j_2},c}$ through the geometric mean of the individual responses collected (Eq. (3)). In turn, these values were used to determine the weights w_{I_j} of the n indicators included in the refined list through the application of Eq. (3).

$$w_{I_j} = \frac{\sum_{j=1}^{n} \frac{1}{\sqrt{\sum_{j=1}^{n} x_{I_{j_1}I_{j_2},c}}}}{\sum\sum_{j=1}^{n} \frac{1}{\sqrt{\sum_{j=1}^{n} x_{I_{j_1}I_{j_2},c}}}} \Leftrightarrow x_{I_{j_1}I_{j_2},c} = \left(\prod_{k=1}^{p} \ln x_{I_{j_1}I_{j_2},e_k}^{\,w_{e_k}}\right)^{1/\sum_{k=1}^{p} w_{e_k}} \tag{3}$$

3.4.3. Assessment of the alternatives across the refined list of indicators

The evaluation of the contribution of the alternatives depicted in Fig. 3 to sustainability across the refined and weighted indicators was accomplished using the TOPSIS method [53]. This technique consists of determining the closeness of the roof types (A_i) to the positive and negative ideal solutions to this MCDA problem according to the following steps:

1 Determine the ratings r_{ij} of each alternative A_i across the indicators I_j through engineering calculations and/or based on specialised literature.
2 Normalise the ratings r_{ij} (n_{ij}) to enable their joint processing according to Eq. (4), which prevents the rank reversal of alternatives by yielding the most suitable alternative to the problem in absolute terms ($\max_i z_j$ and $\min_i z_j$) [54].

$$n_{ij} = \begin{cases} \frac{r_{ij}}{\max_i z_j}, & \text{if } I_j \text{ is a benefit indicator} \\ \frac{\min_i z_j}{r_{ij}}, & \text{if } I_j \text{ is a cost indicator} \end{cases} \tag{4}$$

3 Multiply the normalised ratings n_{ij} by the weights w_{I_j} obtained in Eq. (3) to produce the weighted normalised ratings v_{ij}.
4 Compute the positive (A^+) and negative (A^-) ideal solutions to the MCDA problem as formulated in Eq. (5).

$$A^+ = w_j$$
$$A^- = w_j \frac{n_{ij}\left(\min_i z_j\right)}{n_{ij}\left(\max_i z_j\right)} \tag{5}$$

5 Obtain the Euclidean distance (d_i^+ and d_i^-) from each alternative A_i to A^+ and A^-, according to Eq. (6).

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^+)^2}$$
$$d_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_j^-)^2} \tag{6}$$

6 Compare the Relative Closeness (RC_i) between each alternative A_i and the ideal solution through Eq. (7), such that $0 \le RC_i \le 1$. Hence, the higher the RC_i of an alternative, the more that alternative contributed to sustainable development.

$$RC_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{7}$$

4. Results and discussion

This section compiles and discusses the results obtained from the sequential application of the Multi-Criteria Decision Analysis (MCDA) framework designed to support the selection of the flat roof types outlined in Fig. 3 across the indicators listed in Table 1 and under the climate scenarios depicted in Fig. 2.

4.1. Refinement of the initial list of indicators

The number of questionnaires collected from all the experts addressed was 23, which involved a response rate of 46% in comparison with the original sample. Still, this value kept meeting the frequent sizes (between 20 and 50 experts) suggested in the literature to constitute these panels [49]. Table 3 summarises their opinions about the importance allocated to the list of indicators shown in Table 1, according to the levels of importance defined: very important (VI), important (I), slightly important (SI) and unimportant (UI). For instance, the Albedo coefficient (I_1) was considered very important (VI), important (I) and slightly important (SI) by 7, 9 and 7 experts, respectively. Nobody (0) thought this indicator was unimportant (UI).

One of the first actions undertaken to refine the list of indicators consisted of removing I_8, due to the low importance allocated by the addressees to the reduction of runoff temperature provided by the roofs. Besides, agricultural productivity (I_{10}) was merged with biodiversity (I_9), since the former was the second aspect receiving the lowest score.

Four experts coincided in the need for including a new indicator related to the social use of roofs as spaces for recreation. In this case, the solution adopted affected the existing indicator of aesthetics (I_{15}), which evolved to incorporate these aspects into a new indicator that continued taking into account the impact of roofs on the perception of inhabitants.

Another indicator that was initially disregarded and suggested by several experts concerned the capacity of some roofs for controlling relative humidity through the water lost via evapotranspiration. These

Table 3
Levels of importance allocated by the experts to the initial indicators.

I_j	Indicator	Level of importance			
		VI	I	SI	UI
I_1	Albedo coefficient	7	9	7	0
I_2	Solar power	12	9	2	0
I_3	Carbon sequestration	6	8	8	1
I_4	Embodied carbon	2	12	9	0
I_5	Embodied energy	6	9	8	0
I_6	Runoff attenuation	7	6	8	2
I_7	Water purification	2	7	13	1
I_8	Reduction of runoff temperature	0	3	14	6
I_9	Biodiversity	2	9	12	0
I_{10}	Agricultural productivity	1	4	9	9
I_{11}	Recycled materials	2	11	9	1
I_{12}	Thermal insulation	20	2	0	1
I_{13}	Noise control	8	5	9	1
I_{14}	Life cycle cost	11	11	1	0
I_{15}	Aesthetics	7	9	5	2
I_{16}	Dead load	4	9	9	1
I_{17}	Roof protection	5	11	7	0

comments led to the addition of a new indicator devoted to account for this factor under the climate scenarios considered, resulting in a refined list of 16 indicators.

4.2. Weighting of the refined list of indicators

The levels of importance allocated to the indicators remaining in the list after the refinement process were those provided by the experts in Table 3. Biodiversity and agricultural productivity was scored with the highest level of importance corresponding to one of the two aspects into which this new indicator was originally divided (I_9 and I_{10} in Table 3). Similarly, the social use of roofs was scored with the highest mark between the values assigned to the initial indicator of aesthetics and those associated with the role of roofs as spaces for recreation. Finally, the control of relative humidity provided by roofs was rated as UI, since this was a totally new indicator with no relationship to any of the aspects initially considered in Table 1.

Once the level of importance allocated by each expert to the indicators contained in the refined list was established, 23 pairwise comparison matrices were built according to Table 2. The highest value of $C.R.$ obtained in these matrices through Eq. (1) was 0.083, which ensured the consistency of all the comparisons made by the experts ($C.R. < 0.1$). Then, the importance of the opinions of the experts was computed based on their similarity of thought, as expressed in Eq. (2). In turn, this enabled determining the values reflecting the consensual point of view of the whole panel of experts, such that the resulting comparison matrix was almost perfectly consistent ($C.R. = 0.002$). To end this step, Eq. (3) was applied to calculate the weights of the indicators (Table 4).

On the one hand, the indicators achieving the highest weights were thermal insulation (I_{11}), solar power (I_2) and life cycle cost (I_{13}). These results highlighted the experts' awareness of the need for harmonising the three pillars of sustainability, since these indicators were representatives for the social, environmental and economic dimensions of sustainability, respectively.

Although the relevance of I_{11} and I_{13} as drivers for social comfort and economic development was completely justified, the importance allocated to I_2 might be slightly controversial nowadays, since improvements in the production of photovoltaic energy are currently feasible only at more than 25 °C [55]. However, the weight reached by this indicator is in line with the upward trend in the use of renewable energy, which suggests that the photovoltaic potential of roofs should be increasingly taken into account in the future.

On the other hand, both the water-related indicators (I_6, I_7 and I_8) and biodiversity and agricultural productivity (I_9) were among the aspects obtaining the lowest weights. These were exclusive characteristics of the green roof, such that their reduced importance contributed to increasing the robustness of the results to achieve in subsequent steps, preventing bias towards this alternative.

Table 4
Weights (w_j) of the indicators included in the refined list after the feedback provided by the experts.

I_j	Indicator	Units	w_j
I_1	Albedo coefficient	Dimensionless	0.066
I_2	Solar power	%	0.100
I_3	Carbon sequestration	g C/m^2	0.058
I_4	Embodied carbon	kg CO_2 eq./m^2	0.050
I_5	Embodied energy	MJ/m$_2$	0.060
I_6	Runoff attenuation	%	0.053
I_7	Water purification	Score	0.040
I_8	Relative humidity control	mm/day	0.014
I_9	Biodiversity and agricultural productivity	Yes/No	0.045
I_{10}	Recycled materials	%	0.048
I_{11}	Thermal insulation	cm	0.137
I_{12}	Noise control	t/m^3	0.062
I_{13}	Life cycle cost	€/m^2	0.097
I_{14}	Social use	Score	0.056
I_{15}	Dead load	kN/m^2	0.052
I_{16}	Roof protection	± °C	0.062

4.3. Assessment of the alternatives across the refined list of indicators

The assessment of the sustainability of the roofs represented in Fig. 3 started with the quantification of their performance across the refined list of indicators. The quantification of some indicators stemmed from applying analytical and structural calculations, whilst some others were characterised according to values found in specialised literature. This task was influenced by the climate scenarios described in Fig. 2, since some indicators referred to intrinsic properties of roofs. Table 5 compiles the ratings of the four alternatives considered with respect to the indicators in Table 4.

The Albedo coefficient (I_1) only depends on the materials forming the roof. In general, common values of Albedo in urban surfaces (pavements and roofs) range from 0.1 to 0.25 [1,56]. Since this study considered white and reflective materials to boost sustainability, the Albedo coefficients for the self-protected, gravel finishing, floating flooring and green roofs were set at 0.5 [57], 0.6 [58,59], 0.3 [60] and 0.275 [61], respectively.

The rating of the self-protected, gravel finishing and floating flooring roofs in terms of solar power (I_2) was 0%, since the effect of these alternatives on photovoltaic cells is negligible. Instead, the performance of photovoltaic cells in green roofs might vary from 0.08 to 8.3% [62] depending on the weather. Values of 3, 2 and 4% were allocated to the Mediterranean, Oceanic and Continental climates. Carbon sequestration (I_3) was also exclusive of green roofs. According to the Sedum extensive green roof defined in Fig. 3, a value of 375 g/m^2 [63] was adopted to rate the potential of this alternative for this purpose.

The calculation of the embodied carbon (I_4) and energy (I_5) was undertaken using the Inventory of Carbon & Energy (ICE) [64], which contains these data for a multitude of construction materials. There were variations depending on the climate scenario, mainly due to the differences in thermal insulation. The aggregated multiplication of the mass of the layers forming the roofs by their embodied carbon and energy yielded the values shown in Table 5. In those cases in which specific materials were missing in the ICE, the most similar alternatives available were chosen as substitutes.

The only alternative contributing to reducing runoff (I_6) was the green roof; however, its capacity in this sense depends on a variety of

Table 5
Ratings of the roof types across the refined indicators.

I_j	$\min_i z_j$	$\max_i z_j$	Scenario	Roof type			
				Self-protected	Gravel finishing	Floating flooring	Green
I_1	0.100	0.500	All	0.500	0.400	0.300	0.275
I_2	0.000	4.000	*	0	0	0	3
			**	0	0	0	2
			***	0	0	0	4
I_3	0	375	All	0	0	0	375
I_4	35.00	60.00	*	33.59	33.65	51.35	38.81
			**	33.59	34.71	52.41	39.86
			***	34.64	35.76	53.46	39.86
I_5	425.00	725.00	*	365.56	370.28	488.34	412.90
			**	365.56	398.63	516.69	441.25
			***	393.91	426.99	545.04	441.25
I_6	0	60	*	0	0	0	60
			**	0	0	0	35
			***	0	0	0	45
I_7	0	1	All	0.428	0.681	0.528	0.294
I_8	0.0	3.5	*	0	0	0	3.0
			**	0	0	0	3.5
			***	0	0	0	2.5
I_9	0	1	All	0	0	0	1
I_{10}	50.00	100.00	*	79.65	55.27	67.81	87.32
			**	79.65	57.10	69.22	87.76
			***	80.77	58.78	70.52	87.76
I_{11}	7.50	15.00	*	6.28	5.93	5.66	5.34
			**	7.04	6.69	6.42	6.10
			***	7.71	7.36	7.09	6.77
I_{12}	0.800	1.350	*	1.191	1.375	1.325	1.473
			**	1.191	1.311	1.256	1.423
			***	1.128	1.253	1.194	1.423
I_{13}	9.000	12.500	*	8.560	5.359	6.147	5.697
			**	8.160	6.048	5.844	5.307
			***	8.353	6.192	5.941	5.487
I_{14}	0.00	1.00	All	0.00	0.25	0.65	1.00
I_{15}	2.000	4.250	*	2.049	3.447	3.351	4.190
			**	2.049	3.450	3.353	4.193
			***	2.052	3.453	3.357	4.193
I_{16}	0	55	All	55	5	0	0

* Mediterranean.
** Oceanic.
*** Continental.

factors, including pre-existing humidity and rainfall intensity and duration [65–68]. These aspects achieved the following values for the climate scenarios considered [69,70]: Mediterranean (medium, 160 mm/h, low), Oceanic (high, 125 mm/h, high) and Continental (low, 125 mm/h, medium). The correspondence of these values with those reported by Gregoire and Clausen [71] for different green roofs in several cities around the globe led to define a runoff retention potential of 60, 35 and 45% for Valencia, Santander and Madrid, respectively.

The rating of water purification (I_7) was derived from two studies conducted by Mendez et al. [72] and Farreny et al. [73]. Although the cross-sections represented in Fig. 3 were addressed in either one of the two investigations, they both coincided in testing a metallic roof that was taken as a reference. Therefore, those water quality parameters achieving similar values for the metallic roof in both studies (total suspended solids, nitrate and total organic carbon) were used to determine a normalised index for the roofs in Fig. 3, such that the higher this value, the higher water quality.

Relative humidity control (I_8) was another indicator that only affected the green roof, since it depended on the evapotranspiration produced by vegetation. Based on several studies consisting of onsite measurements [74–77], values of 3, 3.5 and 2.5 mm/day were assigned to this indicator under the Mediterranean, Oceanic and Continental scenarios. Similarly, the green roof was the only alternative capable of providing a suitable space for biodiversity and agricultural growth (I_9), resulting in a binary indicator as shown in Table 5.

The percentage of recycled materials (I_{10}) was calculated by comparison with the total volume of the roofs, according to information provided by different manufacturers. Hence, the gravel layer in Fig. 3b) was assumed to come from a quarry, in order to ensure a high Albedo coefficient. Similarly, the sand and cement in the mortar bed shown in Fig. 3c) was considered not recyclable. Instead, all the plastic materials forming the plots in Fig. 3c) [38] and the waterproofing [78] and thermal insulation [79,80] layers were 100% recyclable, as well as the substrate in Fig. 3d), which stemmed from a combination of recycled aggregates, compost and inert soil [41–43]. The percentage of recycled aggregates in the concrete for slope screed and the concrete floor tiles in Fig. 3c) was set at 65 [81] and 50% [34,37], respectively.

The thickness of the thermal insulation layer (I_{11}) was calculated as specified in the Spanish Technical Building Code [82], whereby the building envelope must meet certain requirements in terms of thermal transmittance according to its surrounding climate, such that the limits for Valencia, Santander and Madrid were set at 0.45, 0.41 and 0.38 m^2 k/w, respectively. The comparison between these values of thermal transmittance and the aggregate of the thermal conductivity of the layers [83] yielded the thickness of the thermal insulation layer in the three climate scenarios considered.

The acoustic insulation responsible for noise control (I_{12}) was determined from the density of 1 m^2 of the cross-sections represented in Fig. 3 [84]. In turn, this density was computed from the thickness and specific weight of the layers, which were established from data acquired both from manufacturers and the catalogue of constructive elements found in Spanish standards [83].

In contrast with previous studies where the calculation of the life cycle cost of roofs (I_{13}) included their energetic, hydrologic and environmental benefits, this value was only evaluated based on construction, maintenance and demolition costs, since other indirect aspects were addressed through specific indicators (Table 4). Hence, I_{13} was calculated as annual €/m^2 according to two construction cost databases [85,86] and considering a lifetime for the self-protected, gravel finishing, floating flooring and green roofs of 15, 25, 30 and 50 years, respectively [87].

The indicator about the social use (I_{11}) of the roofs was scored according to reasonable assumptions in what concerns their role as spaces for recreation and aesthetic enhancers. Consequently, the self-protected, gravel finishing, floating flooring and green roofs were rated with scores of 0, 0.25, 0.65 and 1, based on their trafficability and contribution to improving the quality perception of the urban landscape.

Similarly to the process adopted for characterising I_{12}, the dead load of the roofs (I_{15}) was determined as the aggregate of the specific weights and thicknesses of their layers. Finally, the protection of the waterproofing membrane (I_{16}) was rated according to the thermal amplitude of this layer, which was 0, 5 or 55 °C depending on the type of roof [33] (Table 5).

The sequential application of the steps of the TOPSIS method as specified in Eqs. (4)–(7) enabled normalising and weighting the ratings included in Table 5, as well as computing the Relative Closeness (RC_i) between the alternatives under evaluation and the ideal solution to this MCDA problem. Fig. 4 shows the values of RC_i achieved by each alternative under the different climate scenarios considered.

The results illustrated in Fig. 4 demonstrated that the green roof was by far the most sustainable solution under all climate scenarios, despite being the cross-section providing the worst scores in terms of Albedo coefficient (I_1), water purification (I_7) and dead load (I_{15}). The second best alternative was the floating flooring roof, whilst the self-protected and gravel roofs achieved the lowest values of RC_i in all cases.

Although the green roof achieved the first position in all scenarios, the scores reached by the alternatives varied depending on the climate conditions. Hence, the four roof types achieved their maximum degree of sustainability under the Mediterranean climate, probably due to its lower thermal insulation requirements, which resulted in more

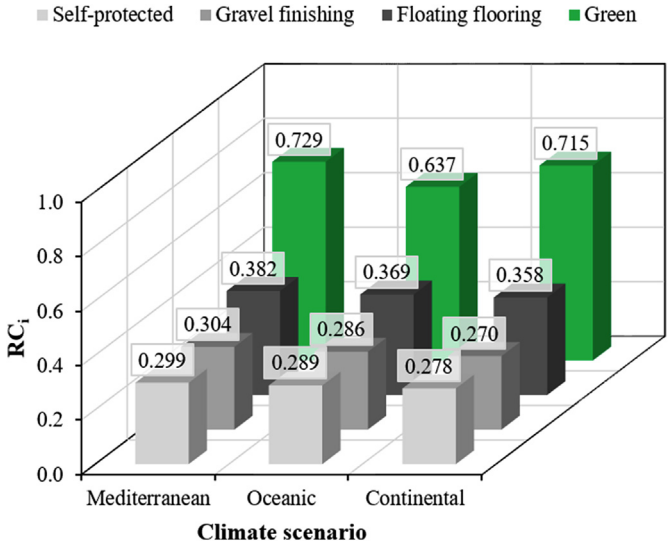

Fig. 4. Relative Closeness (RC_i) between the roof types and an ideally sustainable solution.

favourable values across several indicators. The minimum contribution to sustainability of the green roof stemmed from the Oceanic climate, since its exclusive indicators were less beneficial in Santander. Instead, the remaining alternatives reached their lowest values of RC_i under the Continental climate, since this was the most demanding situation in terms of thermal insulation.

To guarantee the validity of these inferences, a sensitivity analysis was conducted to check the influence of the weights in Table 4 on the results, since the subjectivity inherent to the opinions provided by the experts was a source of uncertainty for the values of RC_i achieved. To this end, five alternative weighting scenarios whereby the indicators were grouped into Energy (I_1, I_2 and I_{11}), Environment (I_3, I_4, I_5 and I_{10}), Water (I_6, I_7 and I_8), Quality of Life (I_9, I_{12} and I_{14}) and Resource Efficiency (I_{13}, I_{15} and I_{16}) were proposed. Hence, the values in Table 4 were systematically modified in each of these scenarios by establishing a predominance of one of the groups, whose weight was set at 0.4, over the others, which weighted 0.15 each. The reapplication of the TOPSIS method with these weights yielded the results shown in Fig. 5, which confirmed the supremacy of the green roof alternative.

One of the main reasons behind the superiority of the green roof related to its exclusive benefits, since only this alternative contributed to 5 of the 16 indicators in Table 4: solar power (I_2), carbon sequestration (I_3), runoff attenuation (I_6), relative humidity control (I_8) and biodiversity and agricultural productivity (I_9). Another aspect justifying the preponderance of the green roof was its extended lifetime, which allows a gradual amortisation of its high initial investment, yielding the lowest values in terms of lifecycle cost (I_{13}). Finally, this alternative also highlighted by its thermal and acoustic benefits in comparison with the other roof types, as well as by its potential for including recycled materials.

As for the other alternatives considered, the Water and Quality of Life weighting scenarios highlighted the runoff purification potential and both the acoustic insulation and aesthetic potential provided by the gravel finishing and floating flooring roofs. Moreover, the reduced dead load (I_{15}) transmitted by the latter alternative to the underlying structure, as well as its competitive values in terms of lifecycle cost (I_{13}) and roof protection (I_{16}), narrowed the difference with respect to the green roof in the Resource Efficiency scenario. The self-protected solution yielded its highest values of RC_i in the Energy and Environment scenarios, especially under Oceanic and Continental conditions, due to its positive ratings in terms of Albedo coefficient (I_1) and recycled materials (I_{10}).

Overall, the results compiled in Figs. 4 and 5 indicated that there is still room for improvement in the design of sustainable roofs, since the values of RC_i achieved by the green roof were far from a completely ideal solution ($RC_i = 1$). This distance was mainly caused by three indicators across which this alternative was poorly scored: Albedo coefficient (I_1), water purification (I_7) and dead load (I_{15}). Potential solutions to palliate these drawbacks might consist of the use of whiter aggregates, geotextiles or lighter materials in the corresponding layers forming the green roof.

5. Conclusions

The results obtained in this research demonstrated the suitability of the proposed approach to assess the contribution of different roof types to achieving the United Nations Sustainable Development Goals (SDGs). This was accomplished through the development of an ad-hoc Multi-Criteria Decision Analysis (MCDA) framework, which filled a gap in the literature in relation to the existence of a methodology to determine the degree of sustainability of roofs under different climate scenarios, based on their valuation across a series of energetic, hydrologic, environmental, economic, social and structural indicators.

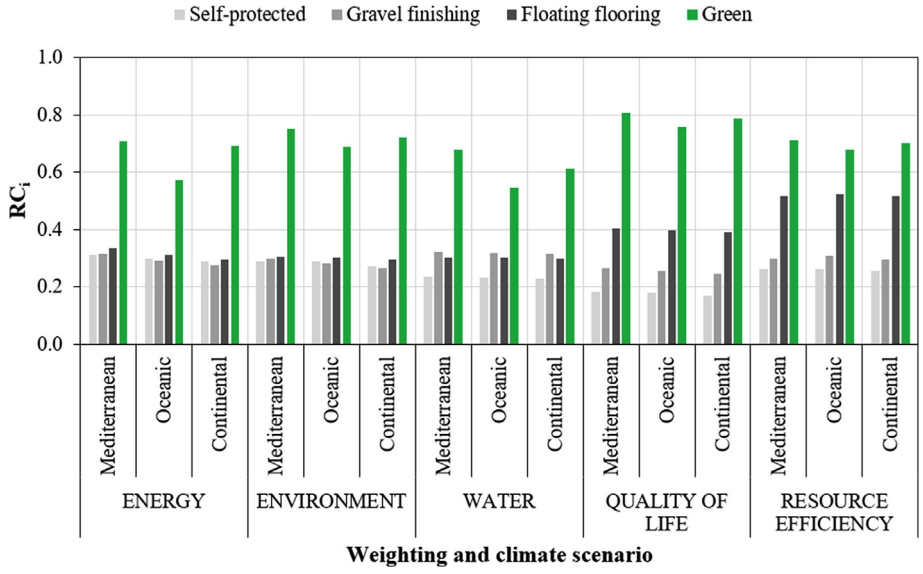

Fig. 5. Values of Relative Closeness (RC_i) of the roof types under the alternative weighting scenarios designed as a sensitivity analysis.

The opinions provided by a panel of international experts in the building industry enabled refining and improving the list of sustainability indicators, ensuring that the academic, professional and institutional points of view were taken into account. The participation of the experts also guaranteed that the weights obtained were representative for the concerns of the building sector in terms of sustainability. In fact, the three most important indicators according to the comparisons made by the experts highlighted the need for integrating the three pillars of sustainable development, since they addressed economic (life cycle cost), environmental (solar power) and social (thermal insulation) issues.

Green roofs emerged as the most sustainable solution under all scenarios, due to their specific energy, water and ecosystem-related services and the cost, recycling and comfort benefits they provide in comparison with conventional alternatives. Still, the design of green roofs should be improved to better address the targets included in the SDGs by including reflective, filter and lightweight materials. As a part of green infrastructure, this type of roofs can also help mitigating Climate Change, which has consolidated as one the humanity's greatest challenges in the future, especially in urban areas.

In consequence, the proposed approach can support the design of urban planning strategies oriented to the progressive replacement of built-up surfaces by green roofs. Their advantages in comparison with conventional roofs should be disseminated and stimulated by public entities and authorities, in order to promote their implementation in both newly constructed and existing roofs. In terms of research, further efforts should be devoted to consider the addition of new indicators and climate scenarios, adapt the proposed framework to other building elements, conduct a more detailed analysis of the effect of some variables (e.g. foliage thickness) and explore complementary lines of investigation, such as sustainable agriculture and food security, structural optimisation based on the influence of the dead load on old buildings or resilience assessment of the different layers forming green roofs.

Acknowledgments

This research was financed by the Spanish Ministry of Economy and Competitiveness with funds from the State General Budget (PGE) and the European Regional Development Fund (ERDF) through the project SUPRIS-SUReS (Ref. BIA2015-65240-C2-1-R MINECO/FEDER, UE).

References

[1] H. Akbari, S. Menon, A. Rosenfeld, Global cooling: increasing world-wide urban albedos to offset CO 2, Climatic Change 94 (2009) 275–286, http://dx.doi.org/10.1007/s10584-008-9515-9.
[2] E. Cuce, S.B. Riffat, A smart building material for low/zero carbon applications: heat insulation solar glass—characteristic results from laboratory and *in situ* tests, Int. J. Low Carbon Technol. (2016), http://dx.doi.org/10.1093/ijlct/ctw009 ctw009.
[3] A.B. Besir, E. Cuce, Green roofs and facades: a comprehensive review, Renew. Sustain. Energy Rev. 82 (2018) 915–939, http://dx.doi.org/10.1016/j.rser.2017.09.106.
[4] The World Bank, Urban population (% of total), https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS, (2016) , Accessed date: 27 March 2018.
[5] R. Emmanuel, E. Krüger, Urban heat island and its impact on climate change resilience in a shrinking city: the case of Glasgow, UK, Build. Environ. Times 53 (2012) 137–149, http://dx.doi.org/10.1016/j.buildenv.2012.01.020.
[6] E. Cuce, Thermal regulation impact of green walls: an experimental and numerical investigation, Appl. Energy 194 (2017) 247–254, http://dx.doi.org/10.1016/j.apenergy.2016.09.079.
[7] H. Frumkin, Urban sprawl and public health, Publ. Health Rep. 117 (2002) 201–217, http://dx.doi.org/10.1016/S0033-3549(04)50155-3.
[8] B. Bhatta, Causes and consequences of urban growth and sprawl, Anal. Urban Growth Spraw. From Remote Sens. Data, Springer-Verlag Berlin Heidelberg, New York (U.S.), 2010.
[9] B. Stone, Urban sprawl and air quality in large US cities, J. Environ. Manag. 86 (2008) 688–698, http://dx.doi.org/10.1016/j.jenvman.2006.12.034.
[10] S.S. Herrera-Gomez, A. Quevedo-Nolasco, L. Pérez-Urrestarazu, The role of green roofs in climate change mitigation. A case study in Seville (Spain), Build. Environ. 123 (2017) 575–584, http://dx.doi.org/10.1016/j.buildenv.2017.07.036.
[11] S. Westra, H.J. Fowler, J.P. Evans, L.V. Alexander, P. Berg, F. Johnson, E.J. Kendon, G. Lenderink, N.M. Roberts, Future changes to the intensity and frequency of short-duration extreme rainfall, Rev. Geophys. 52 (2014) 522–555, http://dx.doi.org/10.1002/2014RG000464.
[12] A.M. Coutts, E. Daly, J. Beringer, N.J. Tapper, Assessing practical measures to reduce urban heat: green and cool roofs, Build. Environ. 70 (2013) 266–276, http://dx.doi.org/10.1016/j.buildenv.2013.08.021.
[13] R. Berto, C.A. Stival, P. Rosato, Enhancing the environmental performance of industrial settlements: an economic evaluation of extensive green roof competitiveness, Build. Environ. 127 (2018) 58–68, http://dx.doi.org/10.1016/j.buildenv.2017.10.032.
[14] United Nations, Sustainable development Goals, https://sustainabledevelopment.un.org/sdgs, (2015) , Accessed date: 27 March 2018.
[15] K. Nassar, W. Thabet, Y. Beliveau, A procedure for multi-criteria selection of building assemblies, Autom. ConStruct. 12 (2003) 543–560, http://dx.doi.org/10.1016/S0926-5805(03)00007-4.
[16] U.G.Y. Abeysundara, S. Babel, S. Gheewala, A matrix in life cycle perspective for selecting sustainable materials for buildings in Sri Lanka, Build. Environ. 44 (2009) 997–1004, http://dx.doi.org/10.1016/j.buildenv.2008.07.005.
[17] F. AL-Nassar, R. Ruparathna, G. Chhipi-Shrestha, H. Haider, K. Hewage, R. Sadiq, Sustainability assessment framework for low rise commercial buildings: life cycle impact index-based approach, Clean Technol. Environ. Policy 18 (2016) 2579–2590, http://dx.doi.org/10.1007/s10098-016-1168-1.
[18] Z.A. Collier, D. Wang, J.T. Vogel, E.K. Tatham, I. Linkov, Sustainable roofing technology under multiple constraints: a decision-analytical approach, Environ. Syst. Decis 33 (2013) 261–271, http://dx.doi.org/10.1007/s10669-013-9446-5.
[19] J. Canto-Perello, M. Martinez-Garcia, J. Curiel-Esparza, M. Martin-Utrillas, Implementing sustainability criteria for selecting a roof assembly typology in medium span buildings, Sustainability 7 (2015) 6854–6871, http://dx.doi.org/10.3390/su7066854.
[20] O. Loikkanen, R. Lahdelma, P. Salminen, Multicriteria evaluation of sustainable energy solutions for Colosseum, Sustain. Cities Soc. 35 (2017) 289–297, http://dx.doi.org/10.1016/j.scs.2017.07.019.
[21] K.-S. Liu, S.-L. Hsueh, W.-C. Wu, Y.-L. Chen, A DFuzzy-DAHP decision-making model for evaluating energy-saving design strategies for residential buildings, Energies 5 (2012) 4462–4480, http://dx.doi.org/10.3390/en5114462.
[22] A. Gagliano, M. Detommaso, F. Nocera, G. Evola, A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs, Build. Environ. 90 (2015) 71–81, http://dx.doi.org/10.1016/j.buildenv.2015.02.043.
[23] D. Kalibatas, V. Kovaitis, Selecting the most effective alternative of waterproofing membranes for multifunctional inverted flat roofs, J. Civ. Eng. Manag. 23 (2017) 650–660, http://dx.doi.org/10.3846/13923730.2016.1250808.
[24] Applicability of multi-criteria analysis methods for the choice of material and technology solutions in building structures, Teh. Vjesn. - tech, Gazette 24 (2017), http://dx.doi.org/10.17559/TV-20150810135440.
[25] J.B. Ellis, J.-C. Deutsch, J.-M. Mouchel, L. Scholes, M. Revitt, Multicriteria decision approaches to support sustainable drainage options for the treatment of highway and urban runoff, Sci. Total Environ (2004) 251–260, http://dx.doi.org/10.1016/j.scitotenv.2004.04.066 334–335.
[26] C. Martin, Y. Ruperd, M. Legret, Urban stormwater drainage management: the development of a multicriteria decision aid approach for best management practices, Eur. J. Oper. Res. 181 (2007) 338–349, http://dx.doi.org/10.1016/j.ejor.2006.06.019.
[27] J. Li, C. Deng, Y. Li, Y. Li, J. Song, Comprehensive benefit evaluation system for low-impact development of urban stormwater management measures, Water Resour. Manag. 31 (2017) 4745–4758, http://dx.doi.org/10.1007/s11269-017-1776-5.
[28] B. Moldan, S. Janoušková, T. Hák, How to understand and measure environmental sustainability: indicators and targets, Ecol. Indicat. 17 (2012) 4–13, http://dx.doi.org/10.1016/j.ecolind.2011.04.033.
[29] G.A. Ban-Weiss, J. Woods, R. Levinson, Using remote sensing to quantify albedo of roofs in seven California cities, Part 1: Methods, Sol. Energy 115 (2015) 777–790, http://dx.doi.org/10.1016/j.solener.2014.10.022.
[30] A. Chazarra, A. Mestre Barceló, V. Pires, S. Cunha, M. Mendes, J. Neto, Atlas Climático Ibérico - Iberian Climate Atlas, Agencia Estatal de Meteorología (AEMET) and Instituto de Meteorologia de Portugal, Madrid (Spain) and Lisboa (Portugal), 2011.
[31] DANOSA, Danopol HS 1.8 Cool Roofing, (2017) http://portal.danosa.com/danosa/CMSServlet?node=210057&lng=1&site=1 , Accessed date: 6 March 2018.
[32] DANOSA, Danopol 250 barrera de vapor, (2018) http://www.danosa.fr/danosa/CMSServlet?node=210070&lng=1&site=1 , Accessed date: 6 March 2018.
[33] A. Sánchez-Ostiz, Cerramientos de edificios: Cubiertas, CIE Inversiones Editoriales DOSSAT 2000, Madrid (Spain), 2003.
[34] CTE, DB SE Acciones en la Edificación, Anejo C: Pesos específicos de los materiales, Código Técnico La Edif, Ministerio de Fomento de España, Madrid (Spain), 2009.
[35] DANOSA, Danofelt PP 200, (2018) http://www.danosa.fr/danosa/CMSServlet?node=710902&lng=1&site=1 , Accessed date: 6 March 2018.
[36] DANOSA, Danopol FV 1.8 Light Grey, http://www.danosa.fr/danosa/CMSServlet?node=210030&lng=1&site=1, (2018) , Accessed date: 6 March 2018.
[37] Previsa, Baldosas filtrantes para terrazas y cubiertas, http://www.previsa.es/terrazas.htm, (2018) , Accessed date: 6 March 2018.
[38] Deck Raiser, Catálogo de productos, Deck Raiser, Santiago de Chile (Chile), 2018.
[39] U. Berardi, A.H. GhaffarianHoseini, A. GhaffarianHoseini, State-of-the-art analysis of the environmental benefits of green roofs, Appl. Energy 115 (2014) 411–428, http://dx.doi.org/10.1016/j.apenergy.2013.10.047.
[40] Growing Green Guide, Weight loading, http://www.growinggreenguide.org/

technical-guide/design-and-planning/site-analysis/weight-loading/, (2017) , Accessed date: 15 March 2018.
[41] C.J. Molineux, A.C. Gange, S.P. Connop, D.J. Newport, Using recycled aggregates in green roof substrates for plant diversity, Ecol. Eng. 82 (2015) 596–604, http://dx.doi.org/10.1016/j.ecoleng.2015.05.036.
[42] A.J. Bates, J.P. Sadler, R.B. Greswell, R. Mackay, Effects of recycled aggregate growth substrate on green roof vegetation development: a six year experiment, Landsc. Urban Plann. 135 (2015) 22–31, http://dx.doi.org/10.1016/j.landurbplan.2014.11.010.
[43] S.B. Mickovski, K. Buss, B.M. McKenzie, B. Sökmener, Laboratory study on the potential use of recycled inert construction waste material in the substrate mix for extensive green roofs, Ecol. Eng. 61 (2013) 706–714, http://dx.doi.org/10.1016/j.ecoleng.2013.02.015.
[44] GeotextileMembranes, Recycled Polypropylene Non-Woven Geotextile Membrane 300gsm, (2017) https://geotextilemembranes.co.uk/index.php/recycled-polypropylene-non-woven-geotextile-membrane-300gsm-price-on-application.html , Accessed date: 15 March 2018.
[45] Projar, Capa de drenaje y retenedora de agua Diadrain 60 para cubierta verde intensiva, https://www.projar.es/productos/productos-jardineria-urbanismo/cubiertas-ajardinadas/componentes-de-cubiertas-ajardinadas/capa-de-drenaje-y-retenedora-de-agua-diadrain-60-para-cubierta-verde-intensiva/, (2016) , Accessed date: 15 March 2018.
[46] Projar, Lámina antirraíces FLW-500 para cubiertas ajardinadas, http://www.projar.es/productos/productos-jardineria-urbanismo/cubiertas-ajardinadas/componentes-de-cubiertas-ajardinadas/laminas-antirraices/lamina-antirraices-flw500-cubierta-ajardinada/, (2016) , Accessed date: 15 March 2018.
[47] D. Jato-Espino, E. Castillo-Lopez, J. Rodriguez-Hernandez, J.C. Canteras-Jordana, A review of application of multi-criteria decision making methods in construction, Autom. ConStruct. 45 (2014) 151–162, http://dx.doi.org/10.1016/j.autcon.2014.05.013.
[48] C.M.D. Black, G.T. Wilson, Assessment of eating disorders: interview versus questionnaire, Int. J. Eat. Disord. 20 (1996) 43–50, http://dx.doi.org/10.1002/(SICI)1098-108X(199607)20:1<43:AID-EAT5>3.0.CO;2–4.
[49] S. Keeney, The delphi technique, in: K. Gerrish, J. Lathlean (Eds.), Res. Process Nurs, seventh ed., John Wiley & Sons, Ltd, Chichester, West Sussex (U.K.), 2015, pp. 267–278.
[50] V. Podvezko, Application of AHP technique, J. Bus. Econ. Manag. 10 (2009) 181–189, http://dx.doi.org/10.3846/1611-1699.2009.10.181-189.
[51] D. Jato-Espino, I. Indacoechea-Vega, L. Gáspár, D. Castro-Fresno, Decision support model for the selection of asphalt wearing courses in highly trafficked roads, Soft Comput. In Press (2018), http://dx.doi.org/10.1007/s00500-018-3136-7.
[52] T.L. Saaty, How to make a decision: the analytic hierarchy process, Eur. J. Oper. Res. 48 (1990) 9–26, http://dx.doi.org/10.1016/0377-2217(90)90057-I.
[53] C.-L. Hwang, K. Yoon, Methods for multiple attribute decision making, Mult. Attrib. Decis. Making. Lect. Notes Econ. Math. Syst, Springer-Verlag, New York (U.S.), 1981, pp. 58–191, , http://dx.doi.org/10.1007/978-3-642-48318-9_3.
[54] M.S. García-Cascales, M.T. Lamata, On rank reversal and TOPSIS method, Math. Comput. Model. 56 (2012) 123–132, http://dx.doi.org/10.1016/j.mcm.2011.12.022.
[55] A. Nagengast, C. Hendrickson, H. Scott Matthews, Variations in photovoltaic performance due to climate and low-slope roof choice, Energy Build. 64 (2013) 493–502, http://dx.doi.org/10.1016/j.enbuild.2013.05.009.
[56] T.R. Oke, The urban energy balance, Prog. Phys. Geogr. 12 (1988) 471–508, http://dx.doi.org/10.1177/030913338801200401.
[57] M. Santamouris, Cooling the cities - a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments, Sol. Energy 103 (2014) 682–703, http://dx.doi.org/10.1016/j.solener.2012.07.003.
[58] R. Levinson, S. Chen, P. Berdahl, P. Rosado, L.A. Medina, Reflectometer measurement of roofing aggregate albedo, Sol. Energy 100 (2014) 159–171, http://dx.doi.org/10.1016/j.solener.2013.11.006.
[59] A.L. Pisello, G. Pignatta, V.L. Castaldo, F. Cotana, Experimental analysis of natural gravel covering as cool roofing and cool pavement, Sustainability 6 (2014) 4706–4722, http://dx.doi.org/10.3390/su6084706.
[60] H. Li, J.T. Harvey, T.J. Holland, M. Kayhanian, The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management, Environ. Res. Lett. 8 (2013) 15023, http://dx.doi.org/10.1088/1748-9326/8/1/015023.
[61] C. Gaffin, R. Stuart, Reza Khanbilvardi, Rosenzweig, Development of a green roof environmental monitoring and meteorological network in New York city, Sensors 9 (2009) 2647–2660, http://dx.doi.org/10.3390/s90402647.
[62] C. Lamnatou, D. Chemisana, A critical analysis of factors affecting photovoltaic-green roof performance, Renew. Sustain. Energy Rev. 43 (2015) 264–280, http://dx.doi.org/10.1016/j.rser.2014.11.048.
[63] K.L. Getter, D.B. Rowe, G.P. Robertson, B.M. Cregg, J.A. Andresen, Carbon sequestration potential of extensive green roofs, Environ. Sci. Technol. 43 (2009) 7564–7570, http://dx.doi.org/10.1021/es901539x.
[64] G.P. Hammond, C.I. Jones, Embodied energy and carbon in construction materials, Proc. Inst. Civ. Eng. - Energy 161 (2008) 87–98, http://dx.doi.org/10.1680/ener.2008.161.2.87.
[65] V. Stovin, G. Vesuviano, H. Kasmin, The hydrological performance of a green roof test bed under UK climatic conditions, J. Hydrol (2012) 148–161, http://dx.doi.org/10.1016/j.jhydrol.2011.10.022 414–415.
[66] J. Mentens, D. Raes, M. Hermy, Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc. Urban Plann. 77 (2006) 217–226, http://dx.doi.org/10.1016/j.landurbplan.2005.02.010.
[67] K.L. Getter, D. Rowe, The role of extensive green roofs in sustainable development, Hortscience 41 (2006) 1276–1285.
[68] J.C. DeNardo, A.R. Jarrett, H.B. Manbeck, D.J. Beattie, R.D. Berghage, Stormwater mitigation and surface temperature reduction by green roofs, Trans. Am. Soc. Civ. Eng. 48 (2005) 1491–1496.
[69] IGN, Humedad relativa media anual, https://www.ign.es/espmap/mapas_clima_bach/Mapa_clima_07.htm, (1999) , Accessed date: 23 March 2018.
[70] CTE, DB HS5 Evacuación de aguas, Apéndice B: obtención de la intensidad pluviométrica, Código Técnico La Edif, Ministerio de Fomento de España, Madrid (Spain), 2017.
[71] B.G. Gregoire, J.C. Clausen, Effect of a modular extensive green roof on stormwater runoff and water quality, Ecol. Eng. 37 (2011) 963–969, http://dx.doi.org/10.1016/j.ecoleng.2011.02.004.
[72] C.B. Mendez, J.B. Klenzendorf, B.R. Afshar, M.T. Simmons, M.E. Barrett, K.A. Kinney, M.J. Kirisits, The effect of roofing material on the quality of harvested rainwater, Water Res. 45 (2011) 2049–2059, http://dx.doi.org/10.1016/j.watres.2010.12.015.
[73] R. Farreny, T. Morales-Pinzón, A. Guisasola, C. Tayà, J. Rieradevall, X. Gabarrell, Roof selection for rainwater harvesting: quantity and quality assessments in Spain, Water Res. 45 (2011) 3245–3254, http://dx.doi.org/10.1016/j.watres.2011.03.036.
[74] F.E. Boafo, J.T. Kim, J.H. Kim, Evaluating the impact of green roof evapotranspiration on annual building energy performance, Int. J. Green Energy 14 (2017) 479–489, http://dx.doi.org/10.1080/15435075.2016.1278375.
[75] E. Voyde, E. Fassman, R. Simcock, J. Wells, Quantifying evapotranspiration rates for New Zealand green roofs, J. Hydrol. Eng. 15 (2010) 395–403, http://dx.doi.org/10.1061/(ASCE)HE.1943-5584.0000141.
[76] O. Schweitzer, E. Erell, Evaluation of the energy performance and irrigation requirements of extensive green roofs in a water-scarce Mediterranean climate, Energy Build. 68 (2014) 25–32, http://dx.doi.org/10.1016/j.enbuild.2013.09.012.
[77] N.D. VanWoert, D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez, L. Xiao, Green roof stormwater retention: effects of roof surface, slope, and media depth, J. Environ. Qual. 34 (2005) 1036–1044, http://dx.doi.org/10.2134/jeq2004.0364.
[78] USEPA, Waste Reduction Model (WARM), (2015) https://www.epa.gov/warm , Accessed date: 26 March 2018.
[79] Cellecta, Extruded Polystyrene XPS – HEXATHERM, (2014) http://www.cellecta.co.uk/cellecta-brands/hexatherm-extruded-polystyrene-xps/ , Accessed date: 26 March 2018.
[80] Insulation Wholesalers Ltd, XPS Polystyrene (Extruded Polystyrene), (2016) http://www.insulationwholesalers.co.nz/product/xps-polystyrene-extruded-polystyrene , Accessed date: 26 March 2018.
[81] M. Sánchez de Juan, Áridos reciclados para aplicaciones de hormigón no estructural, Centro de Estudios y Experimentación de Obras Públicas (CEDEX), Madrid (Spain), 2011.
[82] CTE, DB HE1 Cálculo de parámetros característicos de la envolvente, Ministerio de Fomento de España, Madrid (Spain), 2016.
[83] CTE, Catálogo de elementos constructivos del CTE, Instituto Eduardo Torroja, CEPCO y AICIA, Madrid (Spain), 2010.
[84] M. Connelly, M. Hodgson, Sound transmission loss of extensive green roofs - field test results, Can. Acoust. - Acoust. Can 36 (2008) 74–75.
[85] Activatie, Base de Precios de la Construcción Cantabria 2016-2017, https://www.activatie.org/web/publicacion.php?id=391, (2016) , Accessed date: 26 March 2018.
[86] CYPE, Generador de precios de la construcción, http://www.generadordeprecios.info/, (2018) , Accessed date: 26 March 2018.
[87] T.C. Marrana, J.D. Silvestre, J. De Brito, R. Gomes, Lifecycle cost analysis of flat roofs of buildings, J. Construct. Eng. Manag. 143 (2017) 4017014, , http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0001290.